THE ASTRONOMICAL JOURNAL VOLUME 105, NUMBER 1 JANUARY 1993

VLA OBSERVATIONS OF CANDIDATE SUPERNOVA REMNANTS FROM THE CLARK LAKE 30.9 MHz GALACTIC PLANE SURVEY

P. W. GORHAM,[1] S. R. KULKARNI, AND T. A. PRINCE

Division of Physics, Mathematics, and Astronomy, California Institute of Technology, Pasadena, California 91125

Received 27 May 1992; revised 18 August 1992

ABSTRACT

We report the results of 1464 MHz continuum VLA observations of eight fields containing unidentified small-diameter objects associated with candidate supernova remnants from the Clark Lake 30.9 MHz galactic plane survey. The observations were made in the C configuration, giving a resolution of $\sim$12–20 arcsec, and a sensitivity of typically <0.5 mJy per beam. Polarization measurements were made as well. One of the 30.9 MHz candidates, G41.4+1.2, appears to be confirmed as a supernova remnant by our observations. Of the remaining seven fields observed, three were found to contain small-diameter objects which met some of the criteria for nonthermal origin, but will require further study to evaluate whether they are associated with the candidate supernova remnants. Two of the fields were found to contain groups of unresolved objects consistent with expectations for extragalactic background sources. In these cases the 30.9 MHz observations, which could not resolve the individual sources but would view them as a single extended source, may have mistakenly identified them as possible supernova remnants. Finally, two fields contained bright H II regions.

1. INTRODUCTION

The last decade has produced a large number of sensitive single-dish galactic plane radio surveys including: surveys at 6, 11, and 21 cm with the Effelsberg 100 m telescope (Reich *et al.* 1984, 1990); a linear polarization survey also with the Effelsberg telescope (Junkes *et al.* 1987), a 10 GHz survey with the Nobeyama 45 m telescope (Handa *et al.* 1987); and a 30.9 MHz survey using the Clark Lake interferometer (Kassim 1988a,b). These surveys are beginning to provide a much more detailed picture, both spectrally and spatially, of the brighter structure of the plane down to few arcminute resolution. At wavelengths longer than a few cm, this structure is dominated by the effects of the evolution of massive stars, both through photoionization of interstellar gas, and the catastrophic mass-loss events in novae and supernovae. In spite of the vastly different physics involved, the similarity in the resulting structure formed in these two processes often defeats efforts to easily distinguish the products of stellar collapse—supernova remnants—from the H II regions around hot stars. To further complicate this problem, the same type of stars can yield both structures, and the statistics of superposition of supernova remnants and H II regions are at present poorly known. The resolution and sensitivity of the Very Large Array (VLA) can be powerful in discriminating the two, as shown by the recent efforts of Helfand *et al.* (1989) in which VLA mapping of a number of unidentified galactic plane sources that lacked hydrogen recombination lines was used to successfully identify several new supernova remnants (SNRs).

Source confusion can contaminate nonthermal emission with apparent thermal features, such as recombination lines, and confusion by superposition is most likely for aging remnants, whose surface brightness is low and angular scale large. In such cases it is advantageous to search at meter wavelengths, where H II regions are usually self-absorbed, and the nonthermal spectra of SNR makes them bright enough to stand out above the strong galactic plane background. Such an approach was taken in the Clark Lake (CL) 30.9 MHz galactic plane survey (Kassim 1988a), where 80 candidate SNRs were identified by selecting objects which appeared distinct and resolved by an 11′ by 13′ beam. In fact most of the CL candidates are of angular scales in the 0.5°–1° range, with surface brightnesses that would be among the lowest known for supernova remnants. The CL survey did detect $\sim$90% of the known SNRs surveyed, and many H II regions appear clearly in absorption in the resulting maps. Gorham (1990; hereafter paper I) has studied all of these candidate SNRs by evaluating other survey information in light of the 30.9 MHz results. Paper I concludes that perhaps 16 of the candidates are confirmed by existing survey information, though mapping and understanding their structure may be difficult in many cases because of source confusion. However, the identification of aging SNRs in the plane can provide a unique opportunity to study the merging of a SNR with the interstellar medium.

The results reported here are a first effort at followup observations of these objects. We have taken a somewhat indirect approach: Because the large angular scale of the CL candidates makes them generally difficult targets for VLA observations, we have chosen a subset of CL sources which had associations with smaller scale objects, as noted in paper I. These more compact targets are accessible to short duration VLA observations.

To optimize our use of VLA time, we chose to map the sources only at 1464 MHz, since all of the objects had been

[1]Present address: Department of Physics and Astronomy, University of Hawaii at Manoa, 2505 Correa Rd., Honolulu, HI 96822.

TABLE 1. Observation list.

Field or object	Type[a]	RA (1950)[b] (hh mm ss.s)	Dec (1950)[b] (deg ′ ″)	Time on source (min)
3C286	flux cal.	13 28 49.6	+30 45 58.6	21
3C84	pol. cal.	03 16 29.5	+41 19 51.9	18
1748−253	phase cal.	17 48 45.8	−25 23 17.4	21
1821+107	phase cal.	18 21 41.6	+10 42 43.9	44
G10.3+0.9	source	18 02 10.1	−19 36 37.0	55
G10.5+2.2	source	17 58 32.5	−18 44 56.4	55
G27.3−0.2	source	18 39 04.6	−05 09 07.0	33
G30.7+1.0	source	18 41 18.8	−01 32 20.0	54
G36.0−0.0	source	18 55 30.7	+02 37 24.0	54
4C+05.71	source	18 53 12.9	+05 35 36.0	67
G41.4+1.2	source	19 00 08.0	+08 01 12.0	58
G51.4+0.0	source	19 23 42.9	+16 14 35.0	57

Notes to TABLE 1

[a] cal. = calibrator; pol. = polarization.
[b] Position of field center.

mapped previously in low resolution single dish surveys at 2.7 GHz or higher frequencies, providing information necessary to estimate the spectral index. The inferred spectral indices combined with the presence of linear polarization provided primary selection criteria for discriminating against both galactic H II regions and some steep spectrum extragalactic sources. Combining these criteria with other evaluations based on morphology and measured spectra on the eight fields we have observed has yielded four objects of interest which are described in more detail.

2. OBSERVATIONS AND DATA REDUCTION

The observations were made on 19 January 1991 with the NRAO Very Large Array in the C configuration at a frequency of 1464 MHz and a bandwidth of 50 MHz. Each field was observed with 3–4 "snapshots" of 10–20 min duration each, at varying hour angles over a 12 hr interval. A list of the fields observed along with flux, phase, and polarization calibrators and the total observation time for each is given in Table 1. Hereafter we refer to each field by the name of the primary objects (column 1 in Table 1) toward which the observations were directed. One of the sources that was on our original list, G91.4+0.4, was mapped at 1″ resolution by Green (1990) and found to be a probable extragalactic double source; this object was omitted from the observations.

Amplitude, phase, and polarization calibration were performed at the VLA using the NRAO Astronomical Image Processing System (AIPS). Further visibility editing and subsequent mapping were also done using AIPS at Caltech. The edited final data sets for each field had typically ~30 000 usable independent visibilities. The synthesized beam for the fields varied from 12–18 arcsec FWHM for uniformly-weighted maps; in a number of cases natural weighting or visibility tapering were used to improve the signal-to-noise ratio in the maps. These cases are noted below and the beam sizes are given where they vary from the uniform-weighting case.

We did not attempt to correct for ionospheric Faraday rotation effects, which can be significant for polarization measurements made at 1464 MHz. Thus our measurements of polarization position angle where significant polarization is detected are subject to such errors.

In performing the dirty beam deconvolution, we typically used the CLEAN algorithm, except in a few cases where residual striping was evident in the restored map. Such striping is due to poor interpolation over unsampled regions in the visibility plane. In these cases, which involved low level extended emission, we used a Maximum Entropy deconvolution process (Cornwell & Evans 1985) implemented as the AIPS task VTESS, and it was found to be very effective for this problem.

3. RESULTS

A summary of the results is given in Table 2. Of the eight fields mapped, two contained known supernova remnants, G27.4+0.0 and G30.7+1.0. In the second case, the CL source was in fact identified as the known SNR, and we were primarily interested in investigating the nature of the compact source near the apparent center of the SNR, identified by Reich *et al.* (1986). The field which contains G27.4+0.0 also contains a number of both compact and diffuse H II regions, as well as a portion the 30.9 MHz emission which was identified as a SNR of much larger scale than the 4′ diameter of G27.4+0.0. The remainder of

TABLE 2. Summary of results.

Field or object	Description
G10.3+0.9	resolved 0.7 Jy source, nonthermal, polarized
G10.5+2.2	group of nonthermal point sources; extragalactic?
G27.3−0.2	known SNR; numerous H II regions
G30.7+1.0	known SNR; compact source at center is unpolarized
G36.0−0.0	possible nonthermal bow-shock source
4C+05.71	group of nonthermal point sources; extragalactic?
G41.4+1.2	likely new SNR; diffuse, highly polarized
G51.4+0.0	H II region with possible bow-shock

the fields were selected because they contained objects with which either had apparently nonthermal spectra or measured linear polarization, or both. These characteristics of SNRs are shared with extragalactic sources, so we expected that the fields could contain either; in fact the results of Helfand *et al.* (1989) support these expectations.

Of the six fields that contained primarily unidentified sources, two (G10.5+2.2, and 4C+05.71) contained only groups of unresolved objects consistent with expected numbers of extragalactic sources, using the number densities given by Ledden *et al.* (1980). One of the fields, G51.4+0.0, contained an unusual H II region with a form suggestive of a bow-shock source, but no evidence for polarization. The field which contained G27.4+0.0 was confused by considerable thermal emission and no nonthermal components could be unambiguously identified. The final four fields were found to contain emission that is suggestive of association with a SNR, or a possible pulsar-driven component of a SNR.

For all of the objects reported here searches were made for both x-ray and infrared counterparts, using the *Einstein*, *EXOSAT*, and *IRAS* databases. The results of these searches are reported in paper I, and are noted where relevant below.

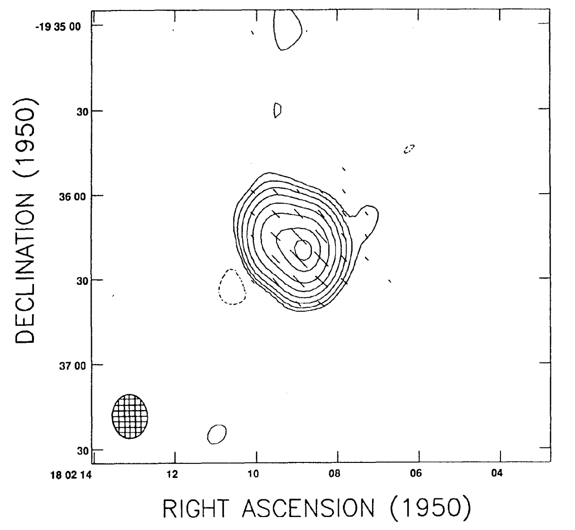

FIG. 1. G10.3+0.9, the central source of the 30.9 MHz candidate SNR of the same name, is shown mapped with the VLA C configuration at 1464 MHz. Contours begin at ±5 mJy, and continue at levels of 10, 20, 40, 80, 160, 320, 475 mJy. Polarization vectors are overlain, with a scale of 1 arcsec=67 μJy/beam. The FWHM beam size is shown in the lower left.

3.1 Sources with Possible SNR or Pulsar-Driven Characteristics

3.1.1 G10.3+0.9, a resolved, polarized object

This object lies at the center of the 30.9 MHz candidate SNR of the same name. Both 1.4 and 2.7 GHz maps made at low resolution (Reich *et al.* 1984, 1990) show a fairly distinct extension off the galactic ridge background which corresponds fairly well to the 30.9 MHz emission (cf. paper I). The compact source is shown in Fig. 1, with polarization vectors overlain. The source is resolved, showing an extension to the NE, apparently aligned with the polarization position angle. The peak polarization is 1.2% at 1464 MHz, and the integrated flux density is 0.70±0.03 Jy, compared to 0.4 Jy at 2.7 GHz, giving a spectra index of −0.8. The source is clearly nonthermal, but it is not as yet well-enough resolved to rule out an extragalactic origin, although the probability of such a bright extragalactic source falling within a few arcmin of the center of the 30.9 MHz diffuse source is of order of few percent, based on standard source count statistics. Sramek *et al.* (1992) report VLA observations which resolve G10.3+0.9 into a distinct double lobe source, with structure that suggests it is probably extragalactic.

A search for diffuse radio emission in the field surrounding this object yielded nothing, but the angular scale and surface brightness evident in the single-dish maps are not suitable for imaging with this VLA configuration. There were also no IR, optical, x-ray counterparts detected for this source.

3.1.2 The compact object at the center of G30.7+1.0

This source was mapped at 4′ resolution by Fürst *et al.* (1987) and found to have a nonthermal spectrum with significant linear polarization at 2.7 GHz, and was thus classified as a new SNR. An unresolved central component evident in the maps of Fürst *et al.* was found to be spectrally similar to the extended emission, and appeared to also be polarized. In the Fürst *et al.* maps it was unclear whether this SNR should be classified as shell-type or composite.

Figure 2(a) shows a 1464 MHz map of this SNR, convolved with a 40″ beam to improve the signal-to-noise ratio over the extended emission. Significant polarization is seen in a broken shell-type structure. Comparison of the polarization position angles with the Fürst *et al.* (1987) map give rotation measures varying from 6–8 rad m^{-2} in the E and SW portions of the SNR, but there is wide variation in other portions of the SNR. This value of the rotation measure could be accounted for by ionospheric effects, but the rotation should then be uniform across the SNR. Thus there appears to be considerable intrinsic Faraday rotation over some portions of the SNR.

A number of compact sources are seen within the bounds of the SNR including the brightest one which was identified by Fürst *et al.* (1987). Two of the compact sources appear to show some linear polarization, but this may be due to juxtaposition with the shell material, which is 5%–10% polarized at 1464 MHz. Surprisingly, the bright central compact source does *not* appear to be significantly polarized at 1464 MHz. Figure 2(b) shows a detail of this object. It is resolved into an ellipsoidal shape, but is at most 0.3% linearly polarized at this wavelength. The probability of finding a 0.7 Jy extragalactic source within a few arcmin of the center of G30.7+1.0 is (as in the case of G10.3+0.9) at most a few percent. The presence of this object is still problematic in this SNR. A pulsar search using the Arecibo telescope has been performed on both

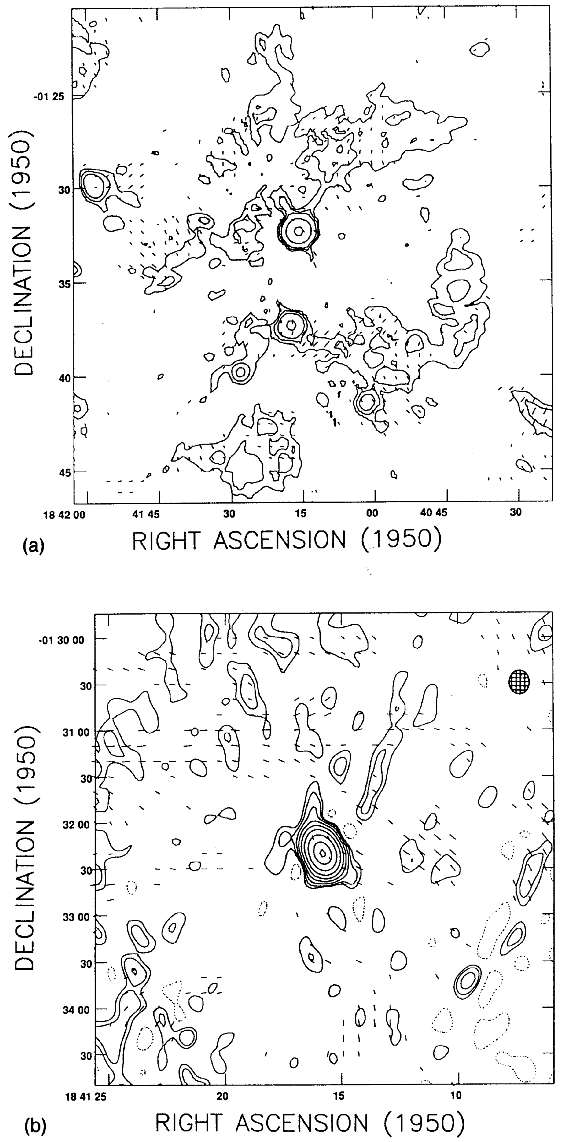

FIG. 2. (a) 1464 MHz map of the known supernova remnant G30.7+1.0, convolved with a 40″ beam to improve the signal-to-noise ratio in the extended emission. Contours are at 2.5, 5, 10, 50, 250 mJy/beam, and polarization vectors are plotted with a length scaling as 0.1 mJy/beam/arcsec of linearly polarized flux density. (b) The central compact source of G30.7+1.0 mapped with a 12″ beam (shown at upper right). Contours at (−1.0, 0.5, 1, 2, 4, 8, 16, 32, 64, 95)×2.83 mJy/beam. Polarization vectors have a linear scale corresponding to 200 μJy/beam per arcsec. The source is slightly resolved, but shows very little, if any, linear polarization.

this source and the compact source 6′ to the south of it, and no pulsations were seen to a limit of 0.4 mJy to a dispersion measure of 30 000 pc cm^{-3}, and pulse frequencies up to 1 kHz (Gorham *et al.* 1992).

3.1.3 G36.3+0.1, a nonthermal possible bow-shock source

This object appears ~6′ north of the center of the G36.0+0.0 field. It is shown in Fig. 3. No significant polarization was detected in the object, but the limits at the 90% confidence level are <30% linear polarization for the extended emission, and <15% for the compact source at the head of the diffuse region. These limits do not exclude a SNR association for this object.

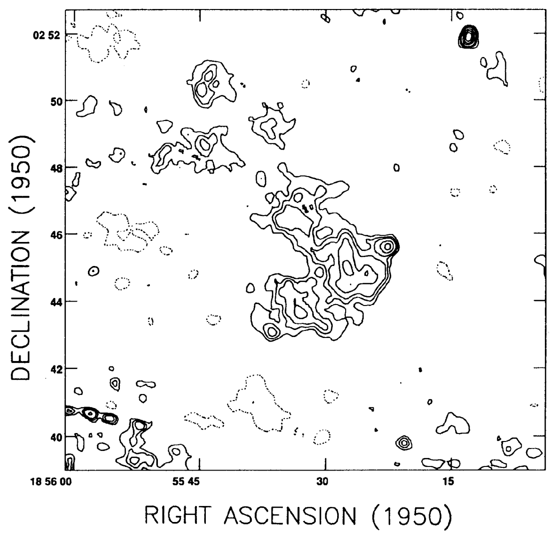

FIG. 3. 1464 MHz map of G36.3+0.1, with contours at 0.6, 0.9, 1.2, 1.8, 2.4, 3.0, 6.0 mJy/beam, with a beam size of ~18″ FWHM. No significant polarization was detected from the source, but the polarization limits are not strong.

The object has the form of a bow-shock source, and appears to be fairly flat spectrum, falling as $\nu^{-0.3\pm0.4}$, based on the single dish measurements of Reich *et al.* (1984), which give 0.4±0.2 Jy at 2.7 GHz and our estimate which gives 0.5±0.05 Jy at 1.4 GHz. The source is not seen at 10 GHz, to a level of about 0.4 Jy (Handa *et al.* 1987).

Hα imaging of this object using the Palomar 1.5 m telescope on 12 June 1991 showed no associated optical emission; in fact, no galactic Hα emission was visible within a 10′ field centered on the object, indicating that the extinction is probably high in this direction. A search of the SIMBAD galactic database, and the NASA extragalactic database (NED) turned up no associations with previously catalogued objects other than the detection by Reich *et al.* (1984).

No recombination lines are reported from this object by Lockman (1989), but the 10 GHz flux density was probably below the recombination line survey limit. Paper I reports that the *IRAS* 60 μm map of this field is confused; the object is at a position in the galactic plane where there is significant large scale thermal emission.

3.1.4 A new low surface-brightness supernova remnant, G41.4+1.2

This field was centered on an unidentified source catalogued by Reich *et al.* (1984) in the Effelsberg 2.7 GHz survey, and also apparent in the 1464 MHz maps of Reich *et al.* (1990), although it was not catalogued explicitly by Reich *et al.* because it was considered too extended for the compact source criterion. The source is associated with the CL source G41.6+1.2. Our 1464 MHz VLA map is shown in Fig. 4, tapered to a 30″ FWHM beam. Although the extended emission is weak, we find from inspection of the

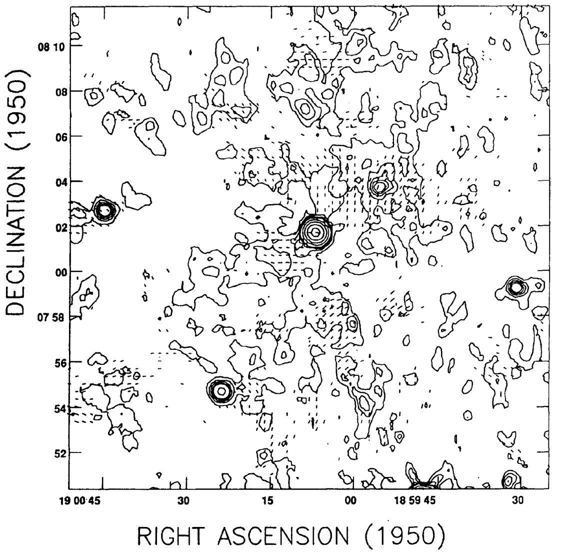

FIG. 4. 1464 MHz map of G41.4+1.2, restored with a 30″ FWHM beam. Contours are at levels of 1, 2, 3, 4, 5, 10, 20, 40, 80 mJy/beam. Polarization vectors scale as 0.1 mJy/beam per arcsec. The presence of considerable polarized extended emission confirms the 30.9 MHz candidate G41.6+1.2 as a new supernova remnant, though the form is not yet distinct enough to classify the type of SNR.

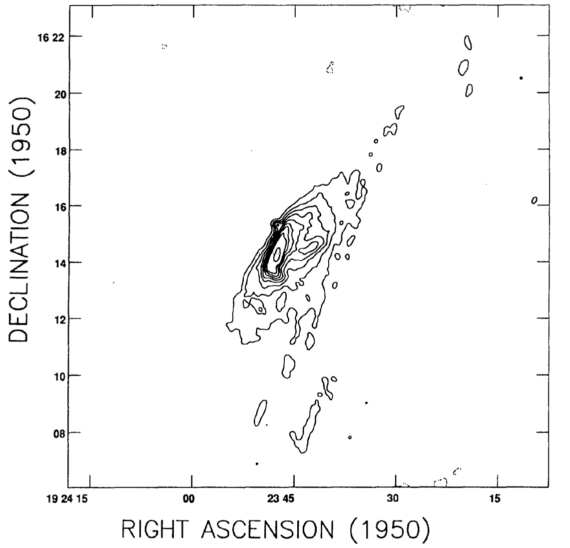

FIG. 5. 1464 MHz map of the source G51.4+0.0, apparently an H II region, but showing an unusual morphology suggestive of an ionization front possibly due to the compact source seen beyond the eastern limb. Contours are at ±5, 10, 15, 20, 25, 30, 35, 40, 60, 80 mJy/beam, with a 15″ FWHM beam. No significant polarization is detected from the source.

visibility data that there is considerable flux density resolved out by the short spacings, and this is also apparent in the polarization visibility data. The extended emission shows a high degree of linear polarization, averaging about 40% in some parts. The strong polarization seen to the northwest of the bright central source is also seen at 11 cm in the survey by Junkes *et al.* (1987) with a similar position angle, suggesting low intrinsic Faraday rotation.

The integrated flux density over a region of ~20′ in diameter is 1.0±0.2 Jy. This value is consistent with single dish measurements at 1464 MHz (Reich *et al.* 1990), which show a peak intensity of 0.4 Jy per 9′ beam for this object, and an extent of ~20′×30′. The largest angular scale to which we were sensitive in these data is ~10′, so there is likely to be additional emission beyond what is seen in our map. Given the 15 Jy flux density estimated for G41.6+1.2 by Kassim (1988a) at 30.9 MHz, it appears that the spectrum is no steeper than $\nu^{-0.5}$.

On the basis of its nonthermal spectrum, polarization, and angular extent, it appears that G41.4+1.2 is a new supernova remnant, although its type is unclear. No *Einstein* or *EXOSAT* x-ray observations covered this region. Radio interferometric mapping with sensitivity to larger angular scale is necessary to delineate the structure of this low-surface brightness SNR. *IRAS* maps of this object show some distinct emission which may be associated with the object (cf. paper I). In this case the IR emission may be associated with shock heating of dust in this region. It should be noted that Arendt (19889) found ~30% of all galactic SNRs had possible associated far-IR emission.

TABLE 3. Compact sources with detected linear polarization.

Source	RA (1950)[a] (hh mm ss.s)	Dec (1950)[a] deg ″	1464 MHz flux density (mJy)	Peak linear polarization (%)	Position angle (deg)[b]
1802−1936	18 02 08.8	−19 36 20	700±30	1.2±0.01	41
1838−0500	18 37 55.6	−05 00 31.1	85±15	3.0±0.3	142
1841−0137	18 41 17.43	−01 37 19.4	70±5	2.0±0.3	175
1856+0241	18 56 06.88	+02 41 10.4	55±10	4.4±0.2	15
1859+0750	18 59 47.57	+07 49 52.0	180±30	1.1±0.2	66
1900+0802	19 00 07.02	+08 01 42.6	129±3	1.2±0.1	78
1901+1300	19 00 46.5	+13 08 00	100±20	2.0±0.5	50
1923+1627	19 23 25.43	+16 25 47.2	51±4	1.2±0.2	151

Notes to TABLE 3

[a] Standard errors in position are typically 1 arcsec in both RA and Dec.

[b] Uncorrected for atmospheric Faraday rotation; systematic errors of ~10° are possible.

There are a number of compact sources within the boundaries of the remnant which appear also to be polarized, only one of which is appreciably resolved with a 15″ beam. The brightest is the compact source 1900+0802 near the center of Fig. 4. It is 1.3%±0.2% linearly polarized, with a flux density of 130 mJy. It does not appear resolved with a 12″ beam.

3.2 An Unusual Source in an H II Region

The CL source G51.4+0.2 was sufficiently close to the catalogued H II region 51.2+0.1 to suggest an association with the compact source G51.4+0.0 that forms the brightest portion of the H II region. This object is shown in Fig. 5. No significant polarization was detected from the region, which has the appearance of an ionization front, with a 20 mJy compact source at the "head" of the front. The probability of detecting a 20 mJy extragalactic source coincident with any portion of this region is probably 10%–20%, but the position of the compact source, and the lack of other detected compact sources in the field suggests that absorption is high and that this source is therefore associated with the extended emission. The position of the compact source is $19^h23^m47.2^s+16°15'17.3''$ (1950), with errors of ~6 arcsec in each coordinate. No association with known stellar or compact extragalactic objects was found. An *IRAS* point source is associated with the center of G51.4+0.0, but the position is somewhat offset from that of the compact source, so it is not known how much of the *IRAS* flux density may be due to this source.

3.3 Compact Sources with Detected Linear Polarization

Table 3 lists all unresolved sources with 1464 MHz linear polarization detected above the 5σ level, which corresponds to typically about 0.8 mJy/beam. Most of these are probably extragalactic sources, but since the fields observed are all in the galactic plane, the possibility of seeing a field pulsar is small but not negligible. The polarizations detected should be considered lower limits to any possible pulsar polarization since there may be beam dilution effects if the source is resolved or superposed on other objects.

We thank the staff of the National Radio Astronomical Observatory Very Large Array for help in calibration of the data. P.G. wishes to acknowledge the support of G. Neugebauer and T. Soifer. This work was supported in part by the National Science Foundation.

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